A Modified Commercial Surveying Instrument For Use as a Spaceborne Rangefinder

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Abstract – We present a summary of the process used to create a reliable, mission-critical sensor from Commercial Off The Shelf (COTS) technology for the Shuttle Radar Topography Mission (SRTM). Measuring the length of the SRTM interferometric baseline to an accuracy of 2mm is a key requirement. An electro-optical rangefinder instrument was recognized as the best option but funds and time were severely constrained. Therefore, the basic approach was to evaluate (though a series of quick tests) a robust commercial surveying instrument, make the necessary modifications for operation in space, followed by a rigorous test program. The result was the delivery of six flight-qualified units with accuracies of 1mm and at a cost significantly lower than that available with traditional methods.

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1. INTRODUCTION

The current push to produce faster and cheaper missions has encouraged non-standard approaches to spaceborne instrument development. In many cases, COTS technology must be considered even for mission-critical applications (some risk is inherent and appropriate in projects of this type). In this paper, we present a summary of one such project. SRTM is scheduled to launch on the shuttle Endeavor in January 2000 and is designed to acquire Interferometric Synthetic Aperture Radar (IFSAR) data covering 80% of the earth's land surface (between +60 deg North and +55 deg South latitudes) [1]. A deployable 60 meter mast (the longest man-made structure ever flown in space[2]) will extend an outrigger radar antenna from the shuttle's payload bay where the main antenna will reside. The SRTM metrology subsystem, the Attitude and Orbit Determination Avionics (AODA), will play a vital role in measuring the total inertial baseline angle to an accuracy of 7 arcsec, baseline length to better than 2 mm, and the platform's orbital position to 1 meter (all accuracies in this paper are at the 1.6σ level unless specified otherwise). The metrology data will be combined with data from two radar instruments to generate an unprecedented near-global digital elevation model with 10 meter relative vertical accuracy at 30 meter postings. For comparison, existing global topographic maps only provide 100 meter vertical accuracy at 1000 meter postings. The resulting data set will be available for myriad uses within the scientific, military, and commercial sectors.

In order to make the necessary baseline length measurements, a precision rangefinder was required. However, the development of a space-qualified rangefinder from "scratch" was determined to be cost and schedule prohibitive. Steps were therefore taken to evaluate a number of commercially available units, resulting in the selection of a near-infrared Electronic Distance Meter (EDM). An extensive qualification program has been completed (including structural, optical, and electronic modifications and environmental testing). In the end, a total of six flight-worthy units were produced, four of which will fly on SRTM.

A brief overview of the SRTM mission and requirements will be presented to lay a foundation for the EDM. We will then describe the EDM and how it works. Significant attention will be focussed on the various modifications required and the test program used to qualify the EDM for space flight. A discussion of the optical design and testing is included, with an emphasis on the problems of beam expansion and alignment. Integration of the EDM into the SRTM/AODA system and operations will also be covered (including the design changes in other sub-systems required to support the EDM). The summary will include lessons-learned and possible future uses for these instruments.

2. SRTM OVERVIEW & REQUIREMENTS

SRTM Overview

SRTM will use IFSAR techniques to map the earth's land topography to unprecedented accuracy on a near-global scale. SAR imagery will provide the two dimensional aspect of the maps. The process for determining the third dimension (height) is as follows. The height of a point on the earth's surface relative to some reference datum can be approximated by the following equation:

$$h_t = h_p - h_s \quad (1)$$

where h_t = height of the target surface feature, h_p = height of the SAR platform above the reference datum (the WGS84 ellipsoid in this case), and h_s = height of the platform above the target surface feature. h_p can be determined directly using Global Positioning System (GPS) receivers on the shuttle (part of the AODA subsystem). h_s can be determined interferometrically to first order as illustrated in Figure 1 and using the following equation [3]:

$$h_s = \rho\cos(\arcsin(\lambda\phi/2\pi B)+\alpha) \quad (2)$$

where ρ = slant range from the radar to the target, λ =wavelength (C & X-band), ϕ =interferometric phase, B = length of the baseline, and α = baseline roll angle.
The first three quantities are known or measured by the radar. The last two are measured by AODA sensors. Errors in baseline length can have profound effect on the resulting accuracy of the topographic maps. For example, a 3 mm error in baseline length knowledge results in a 3 meter height error.

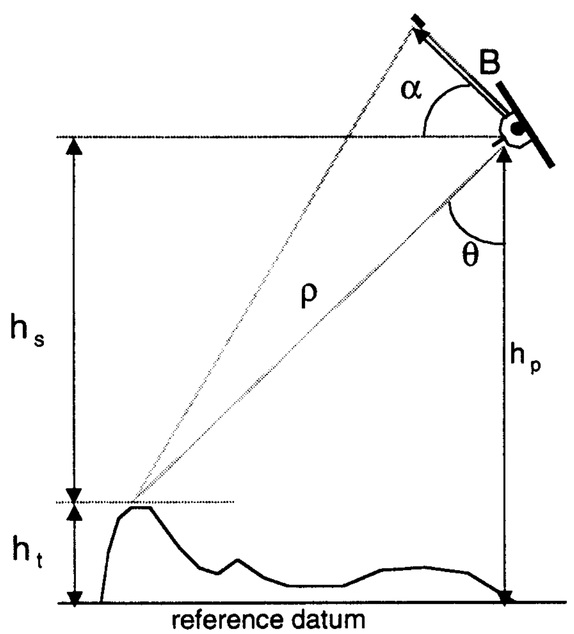

Figure 1 Height Reconstruction Geometry

Baseline Determination

The interferometric baseline is an imaginary line between the inboard and outboard radar antennas (i.e., the separation vector due to the 60 meter long mast). Although the shuttle maintains a fairly stable attitude with respect to the earth's surface (radar beams are pointed 45 deg off the nadir direction), changes in the baseline orientation and length occur constantly due to oscillations of the mast (in response to the shuttle attitude control system) and thermal deformations.

The primary baseline metrology sensor for AODA is a modified CCD star tracker which tracks three LED targets located on the outboard radar antenna at the end of the mast. The target tracker can determine the baseline angle to high accuracy but provides relatively poor accuracy (about 5 cm) for baseline length measurement. If it were static (i.e., a fixed bias), this range error could be removed by calibration. However, the error is really a random, slowly-varying term due to thermally-induced distortions of the main radar antenna structure which supports the mast root (the aluminum structure flexes over time by as much as a few centimeters as the shuttle moves in and out of sunlight). Since the time-constant of these thermal distortions is on the order of tens of minutes, preliminary analysis during the SRTM formulation phase indicated that the error could be modeled using data from a sparsely distributed array of temperature sensors on the mast and supporting structures. Unfortunately, as the SRTM design matured, this assumption was proved to be incorrect given the complexity of the structure. Therefore, the need to directly measure the baseline length arose. This occurred fairly late in the design phase (after the Preliminary Design Review) and initiated a crash effort to procure or develop a flight-worthy rangefinder.

X-band Offset Determination

Even later in the design phase (around the time of project Critical Design Review), another need for rangefinders arose. Since SRTM has two IFSAR instruments, one operating at C-band and the other at X-band with independent antennas, there are really two baselines.
The target tracker and a single rangefinder are capable of measuring the largest component of the baseline length (the 60 meter inboard-outboard antenna separation provided by the mast, designated by the vector **R** in Figure 2). Since these sensors are mounted in a common location on the main antenna array, there are small but significant offsets between this base and the inboard C- and X-band antenna arrays, designated as the vectors **C** and **X** respectively in Figure 2.

C is fairly stable and well-known but **X** is more problematic. Unlike the C-band antenna (a phased array which is steered electronically), the X-band antenna is mounted on the main antenna structure with hinges and

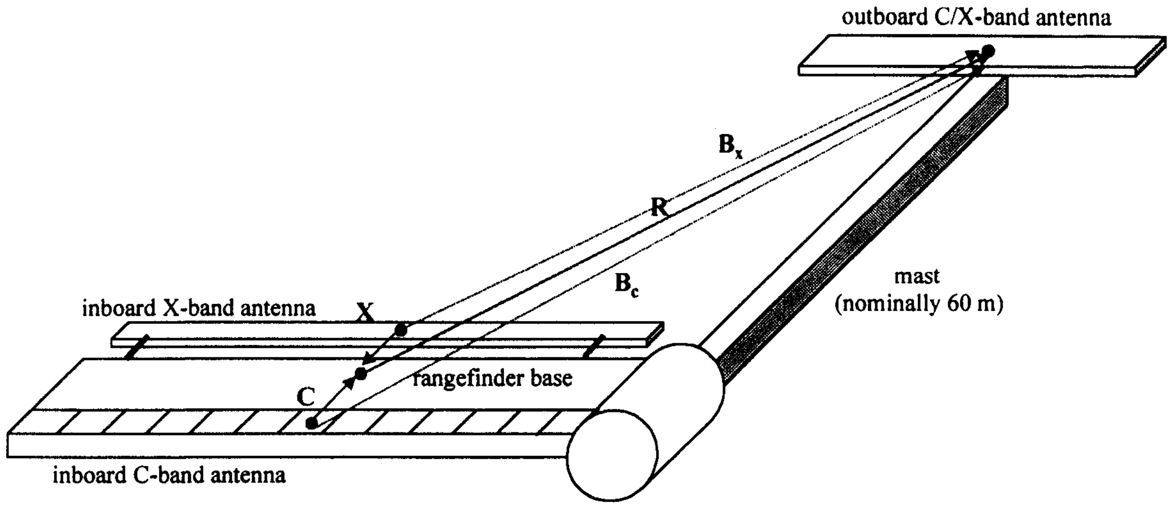

Figure 2 Baseline Determination

deployed via a motor. Although the antenna is not steered during IFSAR operations, thermal distortions similar to those affecting the primary baseline will cause variations in **X**. Since modeling of these distortions across the hinges was not feasible, a requirement was added to directly measure **X** in two degrees of freedom (dof). A simple way to accomplish this is to use two rangefinders to interrogate a single retroreflector on the X-band antenna. If the rangefinders are pointed such that their beams form two legs of a triangle, the individual range measurements can be combined to determine **X**.

EDM Requirements

The resulting rangefinder performance requirements for AODA are as follows:

observable:	range to retro-reflector
resolution:	0.5 mm
accuracy:	2 mm
operating range:	57-61 meters range &
(outboard)	+/- 25 cm lateral
(inboard)	1-2 meters range &
	+/- 15 mm lateral
update rate:	1 sample/5 minutes

This slow update rate is sufficient to meet the Nyquist criteria for the range observables due to the fairly long thermal time-constants involved. The 25 cm lateral motion requirement is driven by the need to accommodate worst-case mast pointing errors. The 15 mm lateral motion requirement is to accommodate X-band antenna pointing errors.

In order to provide reliable operation in space, each rangefinder must meet the following environmental requirements:

Thermal:	-10 to +50 ° C (operating; in vacuum & μ-gravity)	
Vibration:	20-60 Hz	+6dB/octave
	60-300 Hz	0.125 g^2/Hz
	300-2000	-6dB/octave
	overall	8.2 g_{rms}
EMC:	reliable comm over 20 meter cables in the shuttle EMC environment and radar near-fields	
Radiation:	< 10 min data loss/day due to SEE	
	no destructive latchup allowed	
	no TID requirement (11 day mission)	

Based on the performance requirements, a minimum of three rangefinder units would be required (one for **R** and two for **X**). Given the critical nature of **R**, the rangefinder making that measurement must be very reliable (which requires the implementation of either a single high-reliability unit or redundant, less reliable units). The **X** observable is not as critical so a single-point failure there can be tolerated.

Although not listed as a specific requirement, it was highly desirable that the EDMs be eye-safe (i.e., no high powered lasers) in order to avoid additional shuttle safety constraints.

The cost and schedule constraints on rangefinder implementation were more important than usual given the very late addition to the system architecture and proved to be the main driver. We needed to limit the total cost to about $750K and the time from start to delivery had to be within 18 months.

3. Instrument Selection

Based on the above requirements, the preferred approach would be to develop a flight-qualified rangefinder from scratch. Our starting concept was a suite of laser range-finders which would interrogate corner cube retroreflectors on the outboard antenna structure and inboard X-band antenna structure. However, a quick survey of various design groups at JPL indicated that such an approach was not feasible for SRTM. Although the development of a space-qualified laser rangefinder meeting these requirements would not be technically challenging, the cost and time to delivery were excessive (as high as $1500K and 24 months).

In an effort to meet the cost and schedule constraints, we then attempted to find an off-the-shelf solution. One option that was considered was a laser rangefinder developed for the new 100 meter telescope at the National Radio Astronomy Observatory [4]. This rangefinder easily met the SRTM performance requirements but was rejected because of concerns about space qualification and schedule (although a version was adopted for use on GEOSAR, an airborne IFSAR instrument developed by JPL).

We then considered commercially-available instruments. Systems which employed digital photogrammetry were considered but rejected due to complexity, cost, and schedule issues. We finally settled on the type of rangefinders used by the surveying industry.

We were initially allocated a budget of $50K and had two months to select a unit and confirm its suitability for flight qualification. A small team was assembled at JPL consisting of alignment (surveying) experts, packaging engineers, environmental test engineers, and electronic parts specialists. After reviewing the available options from industry, we selected the Leica Distomat DI2002 EDM as the best candidate (see Figure 3). We picked it based on its superior performance, small size, good record of reliability, and general ruggedness. The instrument was designed for surveying. Specifically, it was designed for mounting on a surveying instrument (theodolite) and pointed manually at a retroreflective target that would return significant amounts of energy to the detector. This precise pointing enabled it to operate with a very narrow

Figure 3 Leica Distomat DI2002 EDM

optical beam of low power (no lasing) and thus meet the requirement for being eye safe. Servco Instruments loaned us a unit for testing.

Assessments of DI2002 accuracy and resolution were performed on indoor and outdoor test ranges (the latter to assess performance in full sunlight). Independent methods (including other EDMs and precision tape measures) were used to establish truth data to assess the EDM performance. The DI2002 easily met our performance requirements.

We then completed a series of preliminary environmental tests on the DI2002. A 24 hour thermal-vacuum test confirmed that the unit could operate in the space environment. An acoustic test was used to gain confidence in the EDM's ability to survive the shuttle launch environment. The unit was taken to the Indiana University Cyclotron Facility to undergo 200 MeV proton bombardment testing. Although the EDM experienced a single-event upset that required reloading of an Erasable Programmable Read Only Memory (EPROM), we decided that space-flight was feasible, provided the sensitive components could be identified and replaced (it later turned out that this first test was too rigorous). Tests were also done on a separately purchased filter wheel and motor assembly to assess their sensitivity to vibration. Additional inspections of the unit were performed to assess mechanical and contamination issues.

The overall conclusion of the evaluation was that the unit could be flown if the some reasonable modifications and additional testing were performed (covered in detail in section 5).

4. Instrument Description

The DI2002 measures distance by imposing a sinusoidal modulation on the output of an infrared light-emitting diode, reflecting the radiation from a retroreflector, and comparing the phase of the modulation on the return beam with that of the outgoing one. Transmission and reception are done through separate optical systems. These are fiber coupled to the source and detector respectively. The primary modulation frequency is 50MHz, supplemented by lower modulation frequencies that are used to remove the ambiguity inherent in a modulation wavelength of 6m. Although these lower frequencies are important in surveying, they are not important in this application where only small changes in distance are expected.

An avalanche photo diode detects the return signal. The detector output is mixed with a local oscillator to produce a signal in the kilohertz range that can be processed for the phase comparison. The phase reference is determined by sampling the outgoing beam. An optical element is moved into the outgoing beam by a solenoid and diverts a portion of the energy to the detector. A filter wheel attenuates the optical signal in both the transmitting and receiving paths and serves three purposes: adjusting the signal to an optimum level for measurement, suppressing multiple traversals of the optical path at short ranges, and protecting against sun damage. A permanent-magnet dc motor turns the wheel. The wheel position is sensed by an LED and photodiode combination that measures the attenuation produced by a tapered sensing track near the edge of the wheel.

The operator interface to the commercial instrument is provided by a built-in Liquid Crystal Display (LCD) and keypad or by a computer interface. It is accessed through either of two connectors that also supply the power. The computer interface uses an RS232 format but operates between 0 and 5 volts. The interfaces were modified for this application. The modifications will be described below.

The commercial instrument fits within an envelope 178x57x67 mm oriented with the long dimension in the measurement direction. The objective lenses located at the end of the instrument are 22 mm in diameter and have a center-to-center spacing of 25 mm. The display is located at the opposite end of the case, and the keypad is in the cover. The electronic circuits are located on three boards. The bottom board has the oscillator, LED, and the detector. The latter two are coupled to the bulk optics by optical fibers. The middle board has the processor and memory. The top board has the power-conditioning circuits. The configuration, particularly the optical-fiber coupling, played a pivotal role in both the testing and modification of the instrument.

5. Modifications

EDM Procurement

A purchase was negotiated for six instruments, four to be used for flight and two as flight spares. These were specified to be consecutive serial numbers, subjected to a 320-hour burn-in period, and underwent a full calibration test at the end of the burn-in period. A separate procurement was negotiated for an electronic parts list, and separate purchases were made of additional instruments for development testing as well as of the service software. It should be emphasized as mentioned above that these procurements included a minimal amount of proprietary information. The only information on the circuits was the parts list, and the only information on the software was a list of commands.

Qualification Issues

Qualification issues arose because this is a commercial instrument and could not be flight qualified in the usual manner. The design, both, hardware and software, is proprietary and could not be subjected to the usual failure analysis. In addition the electronic components could not be presumed to be radiation resistant. On the other hand the device was designed as a field instrument able to operate accurately under a wide of temperatures and withstand some amount of rough handling. This gave credence to the idea that it could meet thermal and vibration qualification requirements. The steps necessary to modify the DI2002 that would meet AODA performance and environmental requirements are listed under the following broad categories:

1) Develop an optical configuration that will meet the requirements on ranging accuracy while accommodating the lateral excursion of the target
2) Develop an RS-422 interface circuit (to improve noise immunity in the space environment)
3) Evaluate the sensitivity of electronic components to radiation and replace where necessary
4) Remove/replace any potential contamination (out-gassing) source materials and improve the overall ruggedness of the instrument (conformal coat circuit boards and stake connectors and fasteners)
5) Develop an instrument housing that meets shuttle safety requirements
6) Perform full environmental tests on the finished units (thermal-vacuum, vibration, EMI/EMC).

Optical-System Development

The basic requirement for the optical system was that by a combination of beam spreading and the use of multiple retroreflectors in an array sufficient energy could be returned to the detector for all possible lateral positions of the mast tip. Mass and volume limitations precluded either large spreading optics at the instrument or a very large retroreflector array on the outboard antenna structure. Shuttle safety requirements also played a role limiting the size of individual optical elements.

The development of the optical system required a substantial effort. There were two principal reasons for this. The first was a lack of familiarity with the instrument. For example, the early attempts to measure the field pattern were unsuccessful because the filter wheel was not commanded to a fixed position during the measurements. A more basic difficulty was that attempts to model the optical performance with a standard optical-design program (Code V) were unsuccessful. The optical prescription for the instrument optics had to be assumed and an external system designed to provide the required beam spreading. An experienced optical designer made several attempts to design one- or two element systems that would spread the beam giving a uniform central region and a smooth taper at the edges. All of the designs showed satisfactory calculated performance but poor performance when assembled and placed in front of the instrument. The chief difficulty was a dip in the center of the beam giving a doughnut-shaped pattern.

After several failed attempts to get the desired beam pattern, the decision was made to go with a very weak negative lens as this produced the least central dip in the pattern. This removed the design challenge from the lens and placed it in the retroreflective array, which would be required to have the maximum effective area in order to give sufficient signal strength. The lens chosen had a focal length of -4 meters (-0.25 diopters) and was used on both transmitting and receiving apertures. The lenses were antireflection coated and cemented into individual cells that in turn fitted into the lens cell of the instrument in a manner similar to filters being installed on a camera.

For better security against the effects of launch vibration the auxiliary lenses were coded and individually fitted to the specific instrument and aperture. The front cover of the flight housing secured the auxiliary lenses. This arrangement allowed the lenses to be changed very late in the preparations for flight should that have become necessary.

Once the optical configuration at the instrument had been determined, attention was directed to the retroreflective array. Since attempts at modeling the optical system of instrument plus auxiliary lenses had been unsuccessful, no attempt was made to create an end-to-end model transmitting optics, retroreflector, and receiving optics. The only optical model used was the following: source and receiver apertures separated by 120 m with a retroreflector aperture at the midpoint. Simple ray tracing applied to this model shows that the diameter of the retroreflector aperture should be equal to the diameter of the instrument lenses plus their center-to-center spacing. The energy returned by a larger retroreflector cannot be collected.

A series of tests of retroreflector configurations was used to compensate for the lack of a detailed model. For convenience some of these were conducted at 20 m with scaled instrument and retroreflector apertures. Others were conducted at the full 60 m. Although cube corners are not the only retroreflector configuration, they have several advantages for this application particularly if the open configuration is used. They have low mass, can be arranged in close-packed arrays, and have previously been qualified for space flight. Testing was limited to configurations of open cube-corner reflectors.

The testing, which was quite extensive, was designed to answer the following questions about open cube-corner reflectors. (1) Is there a significant difference in performance between a close-packed array and one in which the reflectors are separated? Open cube-corner reflectors have a hexagonal outline and thus lend themselves to close packing. This puts more reflectors in a given area. On the other hand, it is easier to meet shuttle safety requirements if the reflectors are in individual housings. (2) How is ranging performance affected by translation of an array across a spread beam? In particular, is there a difference between translation parallel to the line between lens centers and translation perpendicular to it? (3) What is the effect of array rotation about a line perpendicular to the line of sight? (4) As a practical matter how much can the diameter of the individual reflector be reduced below the theoretical relationship given above before performance is significantly affected? Since the area available for the array is fixed, reducing the diameter of the individual elements allows more to be accommodated. A balance must be struck between the efficiency of the individual elements and the efficiency of the array.

The conclusions from the testing were the following. (1) There is no difference in performance between a close-packed array and a separated one when they are used with a spread beam. (2) An array can be translated across a spread beam for distances 1.5 to 2 times the width of the array without introducing range changes greater than a millimeter. (3) An array can be rotated through several degrees about a perpendicular to the axis of the beam without introducing range error. The specific tests were limited to 6° as this is greater than angles expected during the mission. (4) The diameter of the individual reflectors can be dropped below the theoretical value by a substantial amount without adverse effect on performance.

This information was utilized fully in the design of the array. The single most important piece of information developed from the testing was that the array could be rotated by several degrees about a perpendicular to the line of sight. This allowed the array to be mounted flat against the outboard structure. Had it proved necessary to mount the array perpendicular to the line of sight, there would have been a nearly insoluble mechanical interference in the stowed position. Several patterns of retroreflector distribution were examined to determine the best fit to the available space. The one selected (Figure 4)

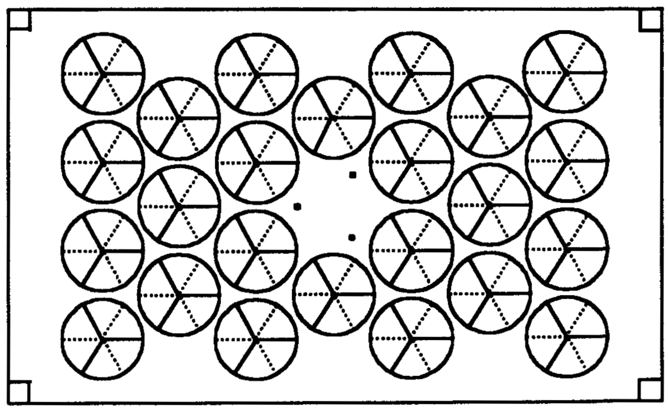

Figure 4 Retro-reflector array

had 25 hexagons in an array that had 4 rows of 4 and 3 rows of 3. The central element of the array was later replaced with a mechanical member to support the cover so that there are now only 24 reflectors. The reflectors have a clear aperture of 43 mm rather than the theoretical 47 mm. PLX, Inc. did the fabrication and mounting of the reflectors. They were bonded to a urethane blanket that was bonded to a backing plate. The array might be described as "almost close-packed" since the individual reflectors did not touch each other. A cover with openings the diameter of the clear aperture of the reflectors enabled the assembly to meet shuttle safety requirements.

RS-422 Communication Interface

When the commercial instrument is used with a computer, an interface box supplied by the manufacturer converts the RS232 interface of the computer to the special format used by the instrument, an RS232 format operating between 0 and 5 volts. Our application required that an interface circuit in the form of a daughter board be added to the instrument. It converts the outgoing signals to RS422 format and performs the inverse operation on the incoming signals. RS-422 is a differential signal and is therefore more resistant to noise than the single-ended RS-232 standard. The daughter board is located in the opposite end of the housing from the lenses in the space made available by the removal of the display and the cover together with its keypad. A 15-pin D connector is mounted in the opening in the housing for the display. This connector is the electrical interface to the rest of the AODA system. The circuit board is mounted immediately behind the connector supported by two brackets attached to the inside of the housing. Connection to the instrument's circuit board is through the connector normally used for the computer interface.

The active components in the interface are an RS422 receiver, 26C32; an RS422 driver, 26C31; and a voltage regulator, RH117. The power for the instrument is supplied through the D connector. It is well conditioned and no further conditioning is needed at the instrument. The instrument itself as distinct from the daughter board is designed for battery operation and is very tolerant of changes in supply voltage.

Radiation Tolerance

Since the DI2002 is a commercial unit there was no reason to expect that its radiation tolerance in any way approached that of a space-qualified instrument. There was, in fact, reason for considerable apprehension as the instrument contained 30 IC's in surface-mount plastic packages. Were it not for the fact that the mission will have a duration of only 11 days and in a low orbit (233 km altitude), the instrument would probably not have been considered. Steps taken to deal with the radiation question included a search for information of the radiation hardness of the components on the parts list and a program of testing.

Three types of radiation tests were used: 200 MeV proton testing previously described, heavy-ion testing at Texas A&M, and fission-fragment testing with Californium 252 done at JPL. Following the initial proton testing and the examination of the parts list a decision was made to replace certain parts and to subject others to additional testing. A 555 timer and two SRAM's were replaced with rad-tolerant versions. The timer was a direct replacement (swapped the CMOS component with its bi-polar counterpart). The replacement SRAM's were pin compatible but not footprint compatible. Their installation on the circuit board presented the major challenge of the internal modifications.

The highest risk remaining parts were identified. These included an ASIC, gate arrays, an EEPROM, a microprocessor, and PROM's. These had to be de-lidded prior to the heavy-ion test (in order for the ions to reach the substrate with sufficient energy to simulate the space environment). The heavy-ion testing was otherwise done with the same configuration used for the proton testing (with boards mounted on a special support so they could be re-oriented for different bombardment geometries without breaking a vacuum in the chamber). The EDM failed with fewer than $3x10^8$ ions/cm^2, an unproductive way to test.

The fission-fragment was done ~~be~~ by irradiating a single component at a time. This extends the test time significantly but in the end proved to be more effective than testing at a remote location. None of the chips showed latchup at 10^5 ions/cm^2, but irradiation of the processor, which was done last, resulted in a permanent miscalibration of the instrument as a result of changes in certain stored parameters. The conclusions of the tests was that the risk of latchup during the mission was too low to be of concern. There is more risk of changes in stored parameters. Some of these, should they occur, can be corrected by reloading the parameter; but some are not accessible for in-flight reloading because the character string is too long for the AODA system. This risk is mitigated in two ways: two instruments are provided for the critical mast-length measurement, and the instruments can be operated intermittently to reduce the total on time.

Miscellaneous Modifications

There were several additional modifications to the instruments. One was the removal of an unneeded external connector. However, one of the external connectors was retained so that the instrument could be returned to its standard configuration for testing. This was desirable because the service software could only be used in the standard configuration. This testing could be done any time during the modification process up to the point of placing the instrument in the enclosure. The following describes the steps of the modification process.

The first step was the removable of volatile and porous materials including sealing compounds, lubricants where accessible, and a dust filter. The cover and display were also removed at this point. The second step was to machine the housing to accept the brackets for the daughter board. This had to be done with great care as many of the components could not be removed from the housing. Following this step the instruments were reassembled and tested to make certain that they were fully functional.

The electronic components were then replaced as described above and the instruments reassembled. The RS-422 daughter boards were installed at this point. When the instruments demonstrated proper operation with the new components, they were released for conformal coating of the circuit boards. Following another functional test, the instruments were assembled for a final time with connectors and fasteners staked. In this final assembly one of the metal spacers between two of the boards that served as a path to case ground was replaced with an insulated one. It was done to meet a shuttle chassis ground isolation requirement.

Instrument Enclosure

Swales Aerospace designed the enclosure for the instrument (Figure 5). The requirements on the design included containment as required by shuttle safety standards, provision for aligning the instrument within the enclosure, and provision for aligning the assembly on the AODA Sensor Panel. The approach was to remove the cover of the instrument, turn the instrument upside down, and secure it in the enclosure by screws into the threaded holes that attach the cover. Since there are 6 holes, 4 were used for hold-down screws and 2 were used for anchoring rods. These rods were threaded into the housing and projected into over-sized holes in the enclosure. Once the alignment of the instrument in the enclosure had been completed, epoxy was injected around the rods and applied to the screw heads to secure the instrument. Push screws in the sides of the case facilitated the lateral adjustment of the alignment. These were left in place and also secured with epoxy.

The alignment of the instrument in the enclosure was the last step in assembly. Figure 6 shows the internal alignment tooling. A three-axis rotary table supported the

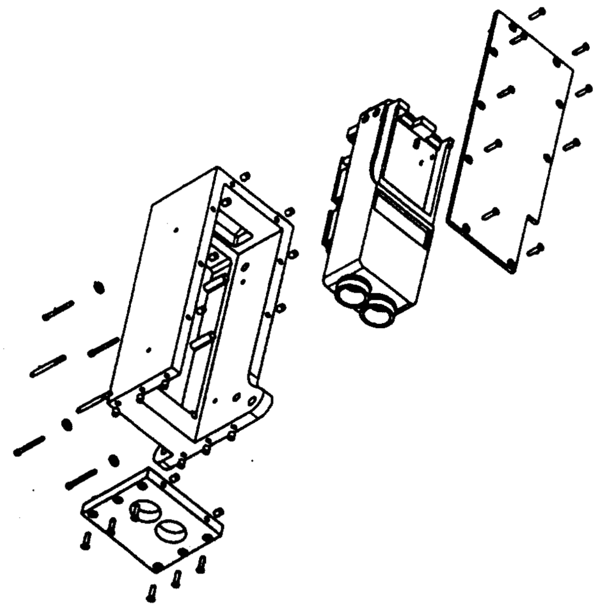

Figure 5 Instrument Enclosure

enclosure. An alignment telescope on a two-axis rotary table was placed at a distance of 10 m. A target mounted in the enclosure marked the centerline of the transmitting lens. The alignment telescope was pointed at it. A mirror with parallel front and back faces was clamped to the front of the enclosure. The alignment telescope was focused on the reflection of itself in the mirror. This was facilitated by a target on the front element of the telescope. The rotary table supporting the enclosure was adjusted until the reflected image fell in the center of the telescope field. This placed the mirror perpendicular to the line of sight of the telescope. The process was repeated until both alignment conditions were satisfied.

The target was then removed and the instrument installed in the enclosure. A target was placed in the transmitting aperture, and the instrument position was adjusted until

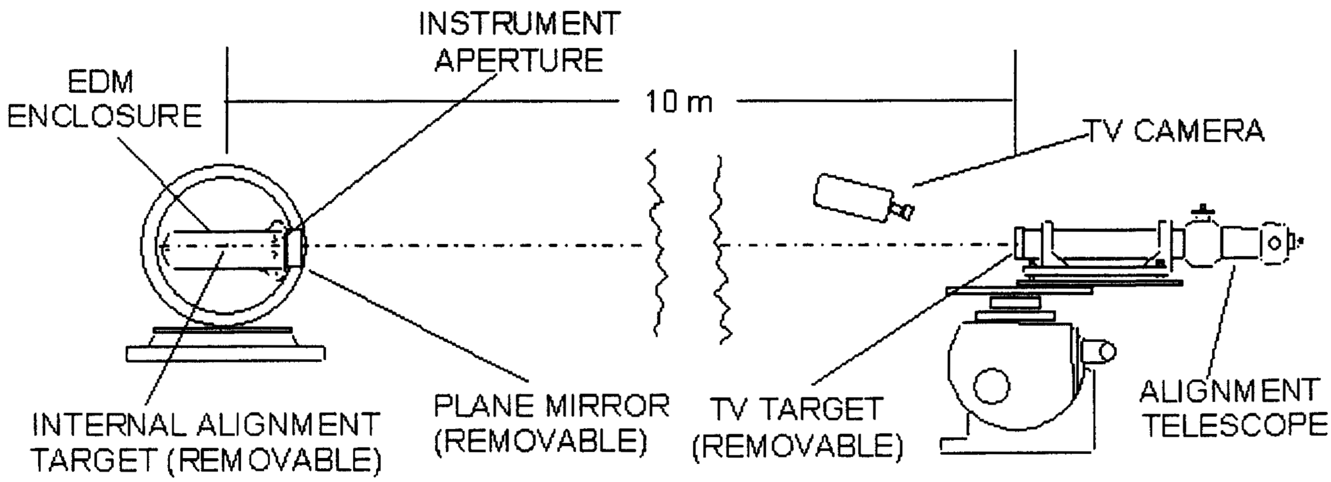

Figure 6 Internal Alignment Test Configuration

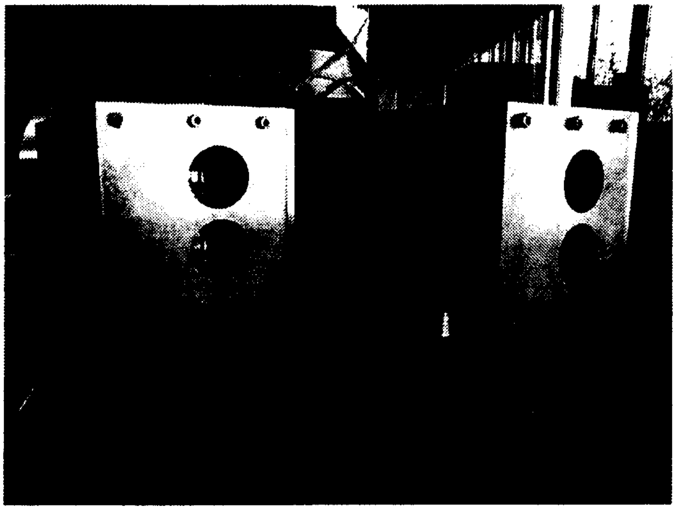

Figure 7 Two completed EDMs

the target was on the line of sight of the telescope. The push screws provided lateral adjustments, and vertical adjustments were done by shimming. A lens cap with a white face was placed on the telescope and the instrument turned on. An infrared viewer was used to observe the beam on the target. The instrument was adjusted in the enclosure to bring the beam to the center of the target. Again the processes was repeated until both conditions are satisfied. The instrument was then secured in its case. Two finished EDMs (undergoing system testing) are shown in Figure 7.

6. Environmental Testing

The completed instruments were subjected to tests for vibration survivability, electromagnetic compatibility, and thermal-vacuum operation. The first was a non-operating test. The other two were operating tests, and the instruments were connected to the AODA Sensor Interface Unit (SIU) which was tested at the same time. The reflector array was subjected to vibration test only.

Vibration

Vibration testing was done at Wyle Laboratories, El Segundo, California. The four flight EDM's, the two flight spares, and the reflector array were subjected to vibration in all three axes. The EDM's were tested for functionality between each axis. The spectrum was 0.0322 g^2/Hz at 20 Hz and 0.2 g^2/Hz between 50 and 250 Hz. The transition from 20 to 50 Hz was 6 dB/octave, and the rolloff from 250 to 2 kHz was -12 dB/octave. All units were fully functional after each test, and no units showed any apparent damage.

Electromagnetic compatibility

EMC testing was done at JPL. This testing is a complex process too long to be described in detail here. Generally, however, the tests covered the following: isolation; conducted emission; conducted susceptibility, both ripple and transients; radiated emissions, both narrow band and broad band; and radiated susceptibility. The isolation test verifies the requirement of separate circuit and case grounds mentioned above. Conducted emissions are the emissions from the device on the power leads. Conducted susceptibility verifies immunity to ripple and transients that may occur on the shuttle power bus. Radiated emissions measure the electric field emitted by the device in the range from 14 kHz to 10 Ghz. There are separate specifications for broad-band and narrow-band emissions. Radiated susceptibility verifies that the device is immune effects of electromagnetic radiation at specified levels in a series of bands from 14 kHz to 15 Ghz (which includes a number of strong fields from the radar instruments and shuttle communication systems). The configuration of four EDM's and the SIU passed all tests. Since this was a test of the instrument design, it was not necessary to test the flight spares.

Thermal-Vacuum Testing

This test was also done at Wyle Laboratories. The four flight EDM's were operated by the SIU, which was also being tested. The two spare units were operated by computers through interface boxes. All six EDM's were mounted on the same cold plate and were pointed at the same retroreflector. The pressure during the test was 1×10^{-4} torr or less. The sequence of temperatures of the mounting plate during the test was the following: 32 hours at 50° C, 32 hours at 20° C, 32 hours at -10° C, and a return to ambient temperature for the end of the test. All instruments operated throughout the test and showed no degradation in performance or appearance.

7. System Integration & Operation

System Mechanical Configuration

The AODA flight system architecture (including the mechanical accommodations for the EDMs) is shown in Figure 8. EDM-1 and EDM-2 are redundant and point at the corner cube array on the outboard antenna to measure the baseline length. EDM-3 and EDM-4 are not redundant and point at the single corner cube on the inboard X-band antenna. The AODA Sensor Panel (ASP) provides structural support for the EDMs, insures they are rigidly connected to the other AODA sensors, and also provides a heat sink.

System (External) Alignment

The EDMs had to be aligned precisely relative to the ASP before launch so that they will point at the deployed corner cubes in flight. It is important to have the EDMs pointed to within a few centimeters of the nominal predicts in order to accommodate in-flight pointing errors in the mast, inboard X-band antenna, and other structures. This external alignment was done using theodolites to measure the orientation of each EDM housing relative to an external reference and individually shimming each until the desired alignment was achieved.

System Electrical Configuration

The flight implementation of the EDM command, data, and power handling interfaces was based on the original, off-the-shelf EDM configuration which used 12V batteries for power and a serial digital communication interface for command and data. Each EDM receives 12 VDC power from the AODA SIU which provides the necessary regulation and filtering of shuttle power. The EDM is controlled by commands via a serial RS-422 communications interface with the SIU. EDM data is sent to the SIU over the RS-422 interface where it is time-tagged and forwarded to other systems for archival and downlink.

System Operation

The EDMs are controlled by commands issued by custom software running on the AODA Processing Computer (APC) in the shuttle's crew cabin. This software executes "macros" in response to operator command (either uplink or onboard) which in turn monitors the EDM data and automatically issues the necessary commands to the EDMs via the SIU. The EDMs can operate in a variety of modes but only 3 modes will normally be used for SRTM and are summarized below.

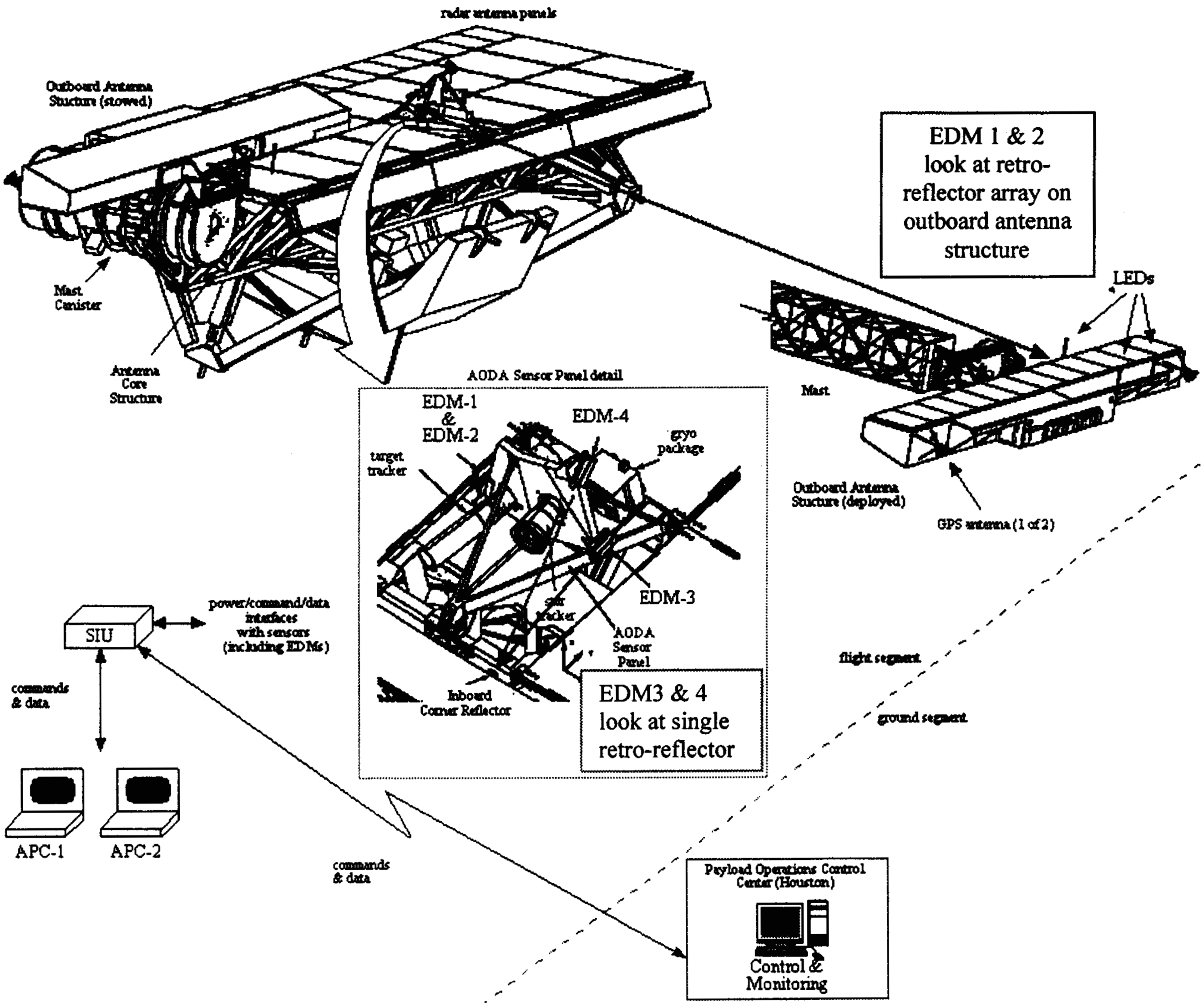

Figure 8 Flight System Configuration

Since the EDM's photodiode can be damaged by accidental direct exposure to sunlight, we have implemented a SAFE mode which when invoked on the APC, issues commands to parks the EDM's internal filter wheel in the maximum attenuation position. This mode can be invoked manually or automatically (the EDM reports signal strength while making range measurements; if the signal exceeds a preset threshold, the APC will trigger the SAFE mode macro). To assist with in-flight antenna alignment, the EDMs can also be placed in TEST mode, during which they only output signal strength measurements at 1 Hz. Finally, in OPERATE mode, the EDMs output range and signal strength measurements. However, this mode requires the APC to repeatedly send a particular command to the EDMs so there's a control loop constantly running in the background to manage this mode. The sequence of events for each EDM when in OPERATE mode is as follows: the APC sends a "GDIST" command to the EDM via the SIU, the EDM performs a range measurement and the associated internal calibrations, the EDM outputs the data to the APC via the SIU, at which time the cycle repeats. Each range measurement cycle typically takes 3-5 seconds to complete.

During mission operations, three of the four EDMs will be activated shortly after launch and will spend most of the mission in OPER mode.

8. Summary & Lesson's Learned

We have produced six flight-qualified rangefinder instruments with accuracies of 1mm over ranges of 1-60 meters in the presence of lateral excursions of 25 cm at sample rates of 0.2 Hz. This was done at a total cost of about $750K and in a period of 18 months. Four of these instruments will be used as part of the critical AODA subsystem on the upcoming SRTM mission and will play a key role in mapping the earth's land topography to unparalleled accuracy.

We have learned that it is possible to modify COTS hardware for reliable space flight instrumentation at a fraction of the cost and time associated with more traditional methods (we cut the expected cost in half and shortened the development time by at least 6 months). However, we also recognize that when limited information is available due to proprietary concerns, a significant effort must be expended to experimentally assess the instrument's readiness for flight. It is also recognized that this approach necessitates some risk-taking. What might be acceptable for one application would be completely inappropriate for another.

In our case, the SRTM mission profile proved a good match for this approach. The mission duration is short (only 11 days) and the environment is relatively benign (low-earth orbit). We were able to take these considerations into account when deciding how to weigh the risks.

Since we will have six flight instruments remaining after the SRTM mission (the two spares plus the four flight units which will return with the shuttle), we have been contacted by several other projects interested in possible re-use of these instruments. One example of this is the Space Technology 3 (ST-3) mission. ST-3 will form an optical interferometer using two spacecraft to provide a long baseline (up to 1 km separation). ST-3 will use a GPS-like system to guide the necessary autonomous formation flying. They would like to add another suite of sensors to independently confirm the formation flying sensor's performance (which involves measuring the spacecraft separation to an accuracy of a few mm). While it may be possible to re-use the SRTM EDMs for this application (particularly if they were intended as an experiment and not mission-critical), there are several issues that must first be assessed. First, the ST-3 mission will be in an earth-trailing orbit (beyond low earth-orbit) and therefore a potentially different radiation and thermal environment. Second, the ST-3 mission will last for several months instead of two weeks (so depending on how often the EDMs were used, there would be limited life considerations, particularly for the mechanical actuators). Third, the different spacecraft separation and lateral excursions would require changes to the expander optics and retro-reflectors.

In any event, this general approach is applicable to other aspects of space flight and we expect to apply it again in the future. We hope we will be able to spend more time with vendors early in the project design phase and gain more insight into their equipment's design and maybe provide some feedback on their processes. If the result of doing these odd-ball projects is boot-strapping more vendors into the space business, so much the better.

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